1   **NON-PROVISIONAL PATENT APPLICATION**

CROSS REFERENCE TO RELATED APPLICATIONS

None.

FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

5

TITLE

10   Telescopic Wing System

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention generally relates to an airfoil with a variable or adjustable lift surface. Specifically, the invention is a wing having one or more telescoping

15   segments deployed via an actuator composed of a material responsive to heat supplied by a fluid or electrically.

2. Background

A telescopic or variable area wing is a device having one or more segments of progressively smaller cross section. It is widely known that such devices improve

20   aerodynamic performance and reduce the total volume required for wing stowage.

The related arts include a variety of telescopic wing geometries and

22   deployment mechanisms. Several noteworthy inventions are reviewed below.

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1   Sarh, U.S. Patent No. 4,824,053, describes and claims a telescopic airfoil with tubular spars. Spars are threaded and telescoping when rotated so as to move in a linear fashion thereby extending and retracting wing segments.

         Gerhardt, U.S. Patent No. 4,181,277, describes and claims a movable wing

5   externally mounted to slide along the trailing edge of a stationary wing. The wing segment is extended and retracted by a single screw jack with traveling nut mounted to the structure on the fuselage centerline above the wing. Screw jack is operated by a hydraulic motor powered by a source of hydraulic fluid driving through a common gearbox.

         Gioia et al., U.S. Patent No. 3,672,608, describes and claims a hydraulic

10   mechanism for supporting a telescopically mounted wing section of an extendible aircraft wing. Hydraulic cylinders, fixedly attached to a telescopic wing section, are in slidable or rolling contact with the other wing section via pistons. The inner wing section is extended from the outer wing section by means of a pair of screw jacks.

         Kapenkin, U.S. Patent No. 2,858,091, describes and claims a retractable wing

15   having a pair of motor driven threaded rods. Threaded rods engage threaded bushings at one end of each of the retractable wings.

         Emmi, U.S. Patent No. 2,743,072, describes and claims a collapsible wing system for aircraft. Wing segments are extended and retracted via a hydraulic means comprising an end closed cylinder and a series of telescopic sleeves each having an

20   external diameter similar to the internal diameter of its adjacent inboard sleeve. Each telescopic sleeve is joined to a wing segment so as to couple sleeve movement to wing

22   segment movement.

1   Makhonine, U.S. Patent No. 2,550,278, describes and claims a variable

surface wing having an inner wing segment with four spars fixed lengthwise along the

wing. Movement of the spars and wing segment attached thereto is achieved via guiding

rollers.

5   Murray, U.S. Patent No. 2,487,465, describes and claims a variable area wing

having an I-beam along its length wherein rollers allow sliding motion between wing

segments. A hydraulically or electrically operated device is used to effect motion between

segments.

        Gibson, U.S. Patent No. 2,423,095, describes and claims a variable area wing

10   having a mechanically driven telescoping shaft within the wing segments. Wing segments

are deployed and retracted via the telescoping shaft.

        Kraaymes, U.S. Patent No. 2,420,433, describes and claims a variable area

wing having panels extended or retracted via screws, worm, chain, hydraulic piston, or

gear segments and spurs. Power for retracting and extending the wings may be supplied

15   manually, electrically, hydraulically, or by engine power.

        Koch, U.S. Patent No. 2,344,044, describes and claims an aircraft wing having

stringers with rollers parallel to spars within the wing. Rollers act as bearings and guides

for the movable wing extensions.

        Fitzurka, U.S. Patent No. 2,249,729, describes and claims a retractable wing

20   tip having a pair of hydraulic reversing jacks in a paired arrangement attached to the wing

tip via stems. Stems communicate movement from the hydraulic reversing jacks to the

22   wing tips.

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1   The referenced inventions rely upon coupled movement between mechanical

elements within a control system powered by various means. Such inventions are heavy,

complex, susceptible to mechanical failure, lack backup operability, and require a

dedicated power source.

5   Shape memory alloys, also referred to as SMAs, are two-phase materials

activated either thermally or electrically. SMAs, one example being Nickel-Titanium,

exhibit a phase transformation in crystal structure when cooled from a high-temperature

form, known as Austenite, to a low-temperature form, known as Martensite. The

temperature at which an SMA remembers its high-temperature form is adjusted by slight

10   changes in alloy composition and through heat treatment. In Nickel-Titanium alloys, the

high-temperature form can be changed from above +100 degrees Celsius to below -100

degrees Celsius. The shape recovery process occurs over a range of just a few degrees.

The start or finish of the phase transformation can be controlled to within a degree or two

if necessary.

15   A coiled SMA may be used as an actuator, as represented in FIGS. 1a-1c. For

example, FIG. 1a shows a coiled SMA tube 1 comprising a coil 4 between an input lead 2

and an output lead 3. The coil 4 is easily expanded lengthwise when the SMA is in its

Martensite phase. The coil 4 reverts to its Austenite phase when heated by a hot fluid 5

therein and recovers its original shape with great force, as represented in FIG. 1b. The coil

20   4 may be cooled by a cold fluid 9, as represented in FIG. 1c, reverting the SMA to its

Martensite phase so that it is again easily deformable.

22   Spring-shaped elements composed of shape memory alloys are described and

1   claimed in two patents. However, the application of a coiled SMA tube 1 for the extension

and retraction of telescopic wings as claimed by the present invention herein is neither

described nor claimed in the related arts.

For example, Baumbick, U.S. Patent No. 6,367,250, describes and claims a

5   micro-actuator comprising a coiled wire composed of shape memory alloy communicating

with and moving a flapper arm to adjust flow between a pair of jet pipes. The coiled wire

is energized by optical energy.

In yet another example, Baumbick, U.S. Patent No. 6,151,897, describes and

claims a micro-actuator to adjust flow between a pair of jet pipes. The coiled wire is

10   heated along its exterior by a hot gas from a gas turbine.

Therefore, what is currently required is a mechanically simple telescopic wing

that minimizes the likelihood of mechanical failure during extension and retraction of wing

segments.

What is required is a mechanically simple telescopic wing having an actuator

15   activated via fluid and electrical means so as to provide redundant control capability over

extension and retraction functionality.

What is require is a mechanically simple telescopic wing having a lightweight

actuator that facilitates extension and retraction functionality between wing segments yet

minimizes power requirements therefor.

20   **SUMMARY OF THE INVENTION**

An object of the present invention is a device capable of extending and/or

22   retracting one or more wing segments in a telescopic fashion so as to minimize the

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1   likelihood of mechanical failure.

A further object of the present invention is a device capable of extending

and/or retracting one or more wing segments in a telescopic fashion when activated via a

heated fluid or electrical current.

5   A further object of the present invention is a device capable of extending

and/or retracting one or more wing segments in a telescopic fashion while minimizing

power requirements therefor.

The present invention is comprised of an inner wing segment, an outer wing

segment, and an actuator. The inner wing segment is telescopically disposed from within

10   the outer wing segment. The actuator is a coiled tube composed of a shape memory alloy.

The actuator is fastened to one end of the outer wing segment and to the opposite end of

the inner wing segment so that the actuator is disposed in a lengthwise fashion along the

length of and within the telescopic wing system. The coiled tube contracts when heated

thereby extending the inner wing segment from the outer wing.

15   Alternate embodiments of the present invention include a resilient element,

one example being a mechanical spring, fastened at one end to the inner wing segment and

the other end to the telescopic wing system. The described arrangement allows the

resilient element to expand when the inner wing segment is extended thereby exerting a

retraction force of lesser magnitude than the actuator. The resilient element retracts the

20   inner wing segment when the coiled tube is cooled and the actuator force is removed.

The coiled tube may be heated by a fluid, including liquids and gases, and/or

22   an electrical current directed through the coiled tube. It is likewise possible to cool the

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1   coiled tube via a fluid. The fluid may be vented after passing through the actuator in an

open loop configuration or re-circulated in a closed-loop system, with or without feedback

control.

     Several advantages are offered by the present invention. The invention

5   minimizes the number of moving elements within the telescopic wing system thereby

simplifying design and function, increasing reliability, and minimizing cost. The invention

minimizes power requirements. The invention provides greater power density and greater

translational capability than comparable size electro-mechanical devices. The invention

weighs substantially less than electro-mechanical devices with comparable performance.

10   Furthermore, the invention is easily adapted to a variety of surface, air, and water craft.

BRIEF DESCRIPTION OF THE DRAWINGS

     The invention will now be described in more detail, by way of example only,

with reference to the accompanying drawings, in which:

FIG. 1a is an elevation view of an exemplary spring-shaped tube composed of a shape

15   memory alloy after deformation when in its Martensite phase.

FIG. 1b is an elevation view of the tube in FIG. 1a after it is heated to its Austenite phase

thereby returning to its original or pre-deformed shape.

FIG. 1c is an elevation view of the tube in FIG. 1b after it is cooled to its Martensite phase

and deformed to a length exceeding that in FIG. 1a.

20   FIG. 2 is a perspective view showing an exemplary telescopic wing in its retracted form

attached to a fuselage.

22   FIG. 3 is a perspective view showing an exemplary telescopic wing in its extended form

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1   attached to a fuselage.

FIG. 4a is a partial cross sectional view of a telescopic wing showing a coiled SMA actuator in its Martensite phase attached to both outer and inner wings and fluid communicated to the actuator via an open-loop system.

5   FIG. 4b is a partial cross sectional view of a telescopic wing showing a coiled SMA actuator in its Austenite phase with inner wing extended and fluid communicated to the actuator via an open-loop system.

FIG. 5a is a partial cross sectional view of a telescopic wing showing a coiled SMA actuator in its Martensite phase attached to both outer and inner wings and fluid

10   communicated to the actuator via a closed-loop system.

FIG. 5b is a partial cross sectional view of a telescopic wing showing a coiled SMA actuator in its Austenite phase with inner wing extended and fluid communicated to the actuator via a closed-loop system.

FIG. 6 is a cross sectional view of an exemplary attachment scheme for securing a coiled

15   SMA actuator to a wing structure.

FIG. 7 is a block diagram of an exemplary embodiment of the present invention showing the control of a paired arrangement of telescopic wings.

REFERENCE NUMERALS

1 Coiled SMA tube

20   2 Input lead

3 Output lead

22   4 Coil

1   5 Hot fluid

        6 Mean diameter, D

        8 Tube diameter, d

        9 Cold fluid

5   10 Structure

        11 Vehicle

        12 Wing wall

        13 Return tube

        14 First end

10   15 Second end

        16 First end

        17 Second end

        18 Fluid

        19 Flexible tube

15   20 Telescopic wing system

        21 Outer wing segment

        22 Inner wing segment

        23 Coiled SMA actuator

        24 Inlet control valve

20   25 Flexible tube

        26 Slot

22   27 Coupler

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20   **DESCRIPTION OF THE INVENTION**

Referring now to FIGS. 2 and 3, an exemplary telescopic wing system 20 of

22   the present invention is shown retracted and extended from a structure 10, respectively.

1   The telescopic wing system 20 is shown having an inner wing segment 22 slidably

disposed within and surrounded by an outer wing segment 21. The inner wing segment 22

resides opposite of the structure 10 about the outer wing segment 21 when deployed.

Exemplary structures 10 include but are not limited to a fuselage, hull, and pressure hull.

5   While the present invention is described having two segments, it is likewise possible for

the described telescopic wing system 20 to include three or more such segments.

          Referring now to FIGS. 4a and 5a, the interior of the telescopic wing system

20 is shown having an inner wing segment 22 of lesser dimensional extent than the outer

wing segment 21 and residing within the cavity formed by the outer wing segment 21. A

10   coiled SMA actuator 23 is shown in its elongated, Martensite phase within the interior of

the inner wing segment 22. One end of the coiled SMA actuator 23 is fastened via a

bracket 28 to the inner wing segment 22 adjacent to the first end 14. The opposite end of

the coiled SMA actuator 23 is fastened via a bracket 28 to the outer wing segment 21

adjacent to the second end 17. A slot 26 is provided along the inner wing segment 22 so

15   as to allow attachment of the coiled SMA actuator 23 to the interior of the outer wing

segment 21. An input lead 45 at one end of the coiled SMA actuator 23 is attached to a

flexible tube 25 via a coupler 27, said elements preferably composed of a heat resistant

material. The opposite end of the flexible tube 25 is attached to an inlet control valve 24, a

non-limiting example being a piezoelectric valve controlled by a micro-controller, via a

20   coupler 27. The inlet control valve 24 communicates fluid 18 from a source, non-limiting

examples including a turbine engine and a hydraulic system. Likewise, the output lead 46

22   at the opposite end of the coiled SMA actuator 23 is attached to a flexible tube 19 via a

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1   coupler 27.

Fluid 18 may be either vented to the exterior of the telescopic wing system 20 or re-circulated so as to pass through the coiled SMA actuator 23 multiple times. In FIG. 4a, the opposite end of the flexible tube 19 is attached to a vent tube 29, via a coupler 27,

5   passing through and fastened to the inner wing segment 22 at the second end 15. The described arrangements permits fluid 18 passing through the coiled SMA actuator 23 to exit the vent tube 29. In FIG. 5a, the opposite end of the flexible tube 19 is attached to a return tube 13, via a coupler 27, passing through and fastened to the structure 10 adjacent to the first end 16. The described arrangement allows fluid 18 passing through the coiled

10   SMA actuator 23 to be reused to further heat or cool the coiled SMA actuator 23. It is likewise preferred that flexible tube 19, return tube 13, and vent tube 29 be composed of a heat resistant material.

Referring now to FIGS. 4b and 5b, the inner wing segment 22 is shown fully extended from the outer wing segment 21 due to compression of the coiled SMA actuator

15   23. A slot 26, as shown in FIGS. 1, 4a, 4b, 5a, and 5b, is provided along the length of the inner wing segment 22 so as to allow unimpeded sliding motion between inner wing segment 22 and outer wing segment 21 adjacent to the coiled SMA actuator 23. The flexible tube 25 should be of sufficient length or extendible so as to accommodate increased distance between input lead 45 and input control valve 24 during extension, as

20   represented in FIGS. 4b and 5b. The flexible tube 19 should also be of sufficient length or extendible so as to accommodate increased distance between output lead 46 and vent tube

22   29 resulting from extension of the open loop embodiment, as represented in FIG. 4b. The

1 flexible tube 19 should likewise be of sufficient length or extendible so as to accommodate

increased distance between output lead 46 and return tube 13 resulting from extension of

the closed loop embodiment, as represented in FIG. 5b.

Attachment of the coiled SMA actuator 23 to inner wing segment 22 and

5 outer wing segment 21 should be sufficiently robust so as to resist mechanical forces

generated during extension of the telescopic wing system 20 and to avoid mechanical

damage to the coiled SMA actuator 23 by attachment hardware. While a variety of

attachment methods and designs are applicable, a u-shaped bracket 28 was placed about

the coiled SMA actuator 23 and fastened to the wing wall 12 via a pair of fasteners 43, as

10 shown in FIG. 6.

An optional resilient element 44 may be employed in embodiments wherein

retraction of the inner wing segment 22 is required. Referring again to FIGS. 4a, 4b, 5a,

and 5b, a resilient element 44 is shown mechanically attached and fixed at one end to the

inner wing segment 22 adjacent to the first end 14 and the opposite end fixed to the

15 structure 10. During extension of the inner wing segment 22, the resilient element 44

expands thereby exerting a restoring force of sufficient magnitude to retract the inner wing

segment 22 when the coiled SMA actuator 23 is cooled. A variety of active and passive

devices are applicable to the present invention, including but not limited to a mechanical

spring and SMA coil.

20 Fluid 18 communicated through the coiled SMA actuator 23 may include a

variety of gases and liquids. For example, hot exhaust emissions from a gas turbine or

22 other engine type may be appropriate where the telescopic wing system 20 is used in a

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1   short-lived craft, one example being an expendable surveillance drone. In multiple use or

long-lived craft, examples including a plane or a submarine, exhaust emissions may be too

corrosive or contain particulates so as to degrade the continuous flow of fluid 18 through

the coiled SMA actuator 23 over time. In the latter applications, it may be desired to use

5   exhaust gases or heat from the gas turbine to heat fuel or other liquid carried by the craft

and thereafter directed through the coiled SMA actuator 23. It is likewise possible to use

the mentioned heat sources to pre-heat air collected from outside the craft and

communicated into the coiled SMA actuator 23.

        In alternate embodiments, the coiled SMA actuator 23 may be heated via

10   ceramic wells along the length of the coiled SMA actuator 23. Ceramic wells similar to

those used in MEMS micro-engines are applicable since sizes smaller than the

cross-section of the coiled SMA actuator 23 are possible.

        In yet other embodiments, the coiled SMA actuator 23 may be heated

electrically via a current. It is further possible to heat the coiled SMA actuator 23 by a

15   resistive heating element along the interior of the coiled SMA actuator 23.

        Electrical heating may also serve as a secondary or backup system to fluid-

based heating so as to improve the overall reliability of the telescopic wing system 20. For

example, dc power may be used to extend the inner wing segment 22 when fluid-based

heating alone is not sufficient or is not operating correctly. Likewise, it is possible for the

20   electrically-based heating system to supplement heating along selected regions of the

coiled SMA actuator 23. In either embodiment, the coiled SMA actuator 23 may be

22   electrically terminated to a power supply through a micro-relay and thereafter coupled to a

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1   controller sensing either failure or limited response and applying back-up electrical power

accordingly.

Referring now to FIG. 7, an exemplary implementation of the present

invention is shown wherein extendible wings are employed in a symmetrically arranged

5   fashion about a left side 31 and a right side 32 of a vehicle 11. A source 30, non-limiting

examples including an electric generator, engine, and compressor with external heater,

communicates either a liquid or gas or current to a pair of regulators 33a, 33b. Regulators

33a, 33b may include a valve, a microprocessor controlled input control valve 24, or a

power relay circuit, as described above. Each regulator 33a, 33b communicates an input

10   stimulus 39a, 39b, either liquid, gas or electricity, into each coiled SMA actuator 35a, 35b,

respectively. Thereafter, each activated coiled SMA actuator 35a, 35b contracts thereby

extending an inner wing segment 36a, 36b from each outer wing segment 34a, 34b. As

previously mentioned, it may be desired to provide a vent 41a, 41b when the input

stimulus 39a, 39b is a liquid or gas. In alternate embodiments, it may be desired that a

15   return 42a, 42b redirect fluid 18 to the source 30 for reuse.

In yet other embodiments, it may be desired to actively control the extendible

wings in a symmetric or asymmetric fashion. An optional sensor 37a, 37b, one example

being a temperature sensitive thin-film array, is used to measure the temperature of each

coiled SMA actuator 35a, 35b. Measurements are communicated to a controller 38 which

20   thereafter communicates an adjustment command 40a, 40b to each regulator 33a, 33b, an

example being a 3-way piezoelectric valve, in a feedback loop architecture of sufficiently

22   high bandwidth to achieve the desired symmetries and asymmetries.

Design Parameters - Coiled SMA actuator 23

Design parameters are estimated for a coiled SMA actuator 23 comprising a coil 4 with an input lead 2 and an output lead 3, as described in FIGS. 1a-1c. The required displacement or stroke (δ) is the total change in length by the coil 4 between Martensite and Austenite phases. The force (P) generated as a result of the prescribed displacement or stroke (δ) is approximated by

$$P = K \, \delta \qquad\qquad (1)$$

where K is the stiffness or the force necessary to yield a unit displacement of the telescopic wing system 20 along the axial length of the coiled SMA actuator 23. Stiffness may be estimated by finite-element analysis or experimental methods understood in the art. The theory for helical-shaped SMA springs described by K. Otsuka and C.M. Wayman in the chapter entitled *Design of Shape Memory Alloy Actuators and Their Applications* in the book entitled *Shape Memory Materials* (published by Cambridge University Press, 1999) is hereby incorporated by reference.

Since force (P) represents the value required to displace the inner wing segment 22 from the outer wing segment 21, the coiled SMA actuator 23 must generate the required force between start and finish temperatures of the Austenite phase.

The primary difference between a helical coil composed of a shape memory alloy and one composed of an"ordinary" spring material is an increase in the modulus of elasticity (or shear modulus) exhibited by the SMA during its phase transformation from Martensite to Austenite. As such, standard spring design equations in *Spring Design Manual*, Second Edition (published by Society of Automotive Engineers, Inc.,

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1   Warrendale, Pennsylvania), *Roark's Formulas for Stress and Strain*, Sixth Edition

(published by McGraw Hill, New York), *Design of Machine Elements*, Fourth Edition

(published by Macmillan, Toronto), and *Mechanical Springs*, Second Edition (McGraw

Hill, New York) are applicable with appropriate adjustment to the modulus so as to

5   account for the phase transformation.

The displacement (δ) by the coiled SMA actuator 23 is related to the force (P)

applied by the following relationship

$$\delta = \frac{8PD^3 n}{Gd^4} \tag{2}$$

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where D is the mean diameter 6 of the coil 4, d is the tube diameter 8 of the coil 4, n is the

number of twists along the coil 4, and G is the shear modulus of the shape memory alloy.

Knowing the shear modulus (G) is temperature dependent and assuming the phase

transformation is complete so that the Martensite volume fraction reduces from 1.0 to 0.0,

15   the shear modulus (G) is equal to the modulus of the Martensite phase prior to

transformation (G_L) and to the modulus of Austenite at the end of the transformation (G_H).

The strength required by the shape memory alloy as a result of the developed

force (P) is estimated based on the shear stress (τ) calculate by

20    $$\tau = \frac{8PD\kappa}{\pi d^3} \tag{3}$$

22   where the stress correction factor (κ) is obtained by the Wahl's formula

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$$\kappa = \frac{4C-1}{4C-4} + \frac{0.615}{C} \qquad (4)$$

and the spring index (C) is

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$$C = \frac{D}{d} \qquad (5)$$

Computational Procedure - Coiled SMA actuator 23 without Leads 2, 3

The magnitude of the force (P) acting on the coiled SMA actuator 23 for a

10   given displacement (δ) is calculated from Equation (1) above. The mean diameter 6, tube

diameter 8, number of twists (n) are limited by the allowable shear stress (τ) and strain (γ)

of the coiled SMA actuator 23. The shear strain (γ_L) in the Martensitic phase is calculated

by

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$$\gamma_L = \frac{\tau}{G_L} \qquad (6)$$

where the shear stress (τ) is the allowable value enabling the calculation of the

transformation induced shear strain in the coiled SMA actuator 23. The shear strain (γ_H)

in the Austenitic phase is calculated by

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$$\gamma_H = \frac{\tau}{G_H} \qquad (7)$$

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1   Accordingly, the shear strain (γ) accumulated as a result of the transformation is

calculated by

$$\gamma = \gamma_L - \gamma_H \qquad (8)$$

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Knowing the shear strain (γ) and two other design parameters (D, d, or n), it is possible to

calculated the third by the following

$$\gamma = \frac{\delta d}{\pi n D^2} \qquad (9)$$

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Design for Prescribed Mean Diameter 6

In some applications, the size of the mean diameter 6 may be limited by design

constraints or considerations. Accordingly, the equations above are transformed to the

following

15   (10)

$$\kappa C^3 = \frac{\pi D^2 \tau}{8P}$$

$$n = \frac{\delta}{\pi C D \gamma} \qquad (11)$$

20   The value of κC^3 is calculated from equation (10) as a function of the allowable shear

stress (τ) and required force (P). Graphs in the reference entitled *Design of Shape*

22   *Memory Alloy Actuators and Their Applications* are used to evaluate the corresponding

1   value of C. Thereafter, the number of twists (n) is determined from equation (11).

Accounting for Effect of Input Lead 2 and Output Lead 3

The displacement due to the input lead 2 (δ_1) and the output lead 3 (δ_2) may

be estimated when the curvature of the leads is disregarded.

5   The stiffness of each lead 2, 4 is calculated by

$$k_i = \frac{\pi d^2}{4} E \frac{1}{L_i} \qquad (12)$$

10   where E is the modulus of elasticity (which varies with temperature), and L is the length of

the corresponding lead 2, 4 and subscript i is 1 for the input lead 2 and 2 for the output

lead 3.

Since input lead 2, coil 4, and output lead 3 are in series, the total

displacement (δ) is given by

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$$\delta = \delta_1 + \delta_s + \delta_2 \qquad (13)$$

where δ_s is the displacement by the coil 4. Equation (13) assumes that input lead 2, coil 4,

and output lead 3 are subject to and activated by temperature producing a complete phase

transformation. Accordingly, since the displacement (δ) is known and the force (P)

20   applied to the coiled SMA actuator 23 is given by Equation (12), it is possible to evaluate

the displacement of the coil 4 from Equation (13) where

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$$\delta_s = \delta - \left| \frac{P}{k_{1L}} - \frac{P}{k_{1H}} \right| - \left| \frac{P}{k_{2L}} - \frac{P}{k_{2H}} \right| \tag{14}$$

The stiffness (κ) of the input lead 2 and output lead 3 is specified for the modulus of

elasticity corresponding to either low or high temperature. The corresponding terms in the

5   right side of Equation (13) reflect on transformation-induced displacements generated in

the straight leads 2, 4, comparable to the evaluation of the shear strain in Equation (8).

Based upon the Equations above, a larger displacement (δ) is achieved by

increasing the number of twists along the coil 4. When the number of twists (n) is

constant, a trade-off between displacement (δ) and force (P) is generated by the coiled

10   SMA actuator 23 suggesting that a larger displacement (δ) may be obtained where the

force (P) requirement is relaxed. In general, the force (P) output by a coiled SMA actuator

23 with a constant prescribed stroke is nearly proportional to the number of twists (n).

However, where the force (P) output is constant, the displacement (δ) is nearly

proportional to the number of twists (n).

15   The description above indicates that a great degree of flexibility is offered in

terms of the present invention. Although the present invention has been described in

considerable detail with reference to certain preferred versions thereof, other versions are

possible. Therefore, the spirit and scope of the appended claims should not be limited to

the description of the preferred versions contained herein.

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